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NASA'S LOW-COST, ONE-MODULE CRASH CUSHION

By

Abraham H. Wilson
Jet Propulsion Laboratory
Pasadena, California

Ruth M. Lizak
SRI International
Menlo Park, California

SRI International

333 Ravenswood Ave. • Menlo Park, California 94025
(415) 326-6200 • Cable: SRI INTL MPK • TWX: 910-373-1246

ABSTRACT

A low-cost, one-module crash cushion has been developed by the National Aeronautics and Space Administration (NASA) as part of its Technology Transfer Program, a program for adapting NASA technology (in this case, the lunar landing impact attenuator) to solve terrerstrial problems in the public sector (in this case, vehicle collisions with tuility poles and trees). The cushion is based on a concept disclosed in NASA Tech Brief 72-10712, wherein many contiguous cylinders or spheres, arranged in multiple strata, attenuate an impact by sequentially crushing.

Cylinders used in the NASA crash cushion are disposable aluminum beverage cans, which were selected because of their low cost and high energy dissipation qualities. The cans are contained in a box-like frame, whose sides slide past the tree or pole as the cans are crushed during an impact. The total weight of the 3-ft. wide/3-ft. high/6-ft. long module is about 300 lb. Total cost for materials is approximately $150.

Crash testing was conducted in accordance wtih the National Cooperative Highway Research Program (NCHRP) Report 153 and Transportation Research Board Circular 191. Tests were made with a live driver at the Orange County (California) Raceway. A steel pole was substituted for the wooden utility pole to prevent erroneous measurements due to shearing of the pole. (Utility poles tend to shear when impact speeds reach about 30 mph.)

With an impact speed of 30 mph, the average G levels experienced by a 4,500-lb. vehicle when colliding with the NASA cushion were 4.7 (head-on), 4.5 (15 deg alongside) and 5.2 (head-on, off center). These levels are well below the NCHRP preferred level of 6.0, and far below the maximum level of 12.0. In a repeat test at a slightly higher speed, the average G level for a head-on collision was still a low 4.9. Extrapolation of these data indicates that the NASA one-module system provides safe cushioning (i.e., less than 12.0 average Gs) to an impact speed of at least 40 mph. For protection from utility poles which shear when hit at about 30 mph, the safety of the device seems assured. In addition, the NASA crash cushion can protect an errant vehicle from collision with any fixed obstruction on winding highways and other roads at speeds of 40 mph or less. Instrumentation of a live driver revealed that, although the driver experienced higher G levels than did the vehicle (averaging 5.5), the levels were well below the NCHRP limits.

I. BACKGROUND

Highway accidents result in thousands of deaths, millions of injuries, and billions of dollars in property damage each year. When a driver cannot perform an attempted maneuver -- whether because of insufficient warning, deficiencies in highway design or maintenance, overestimating the capabilities of the vehicle, or inadequate driving skills -- an accident usually occurs. This report examines only highway design problems and the reduction of highway dangers to the motorist. Specifically, it relates to a crash cushion to protect the out-of-control vehicle from colliding with fixed objects along the roadway.

Collisions with fixed objects such as bridge piers and parapets, stanchions, utility poles, and trees, constitute the fourth largest category for highway fatalities -- approximately 10,000 fatalities per year. Of the 3.1 million motor vehicle accidents that are reported annually, 18%, or 234 million, are off-the-road accidents. To lessen the severity of these accidents, the Highway Safety Program Standard on Highway Design, Construction and Maintenance (27 June 1967) requires "protective devices that afford maximum protection to the occupants of vehicles wherever fixed objects cannot reasonably be removed or designed to yield." Protective devices (i.e., impact attenuators) began to appear on America's highways about 1970.

Statistics for 1975 compiled as part of the Federally Coordinated Program indicated 2,100 fatalities and 56,000 serious injuries for freeway accidents involving fixed objects, and 19,900 fatalities and 311 million serious injuries for nonfreeway off-the-road accidents. (See Tables 1 and 2.) Of these 1.1 million accidents, 391,000 (or 36%) involved trees or utility poles. Only 5% of the fatalities in freeway off-the-road accidents involve trees; however on nonfreeways, trees are involved in 30% of the fatal off-the-road accidents and 33% of the serious injuries.

To protect motorists from injuries resulting from collisions with trees and utility poles on secondary roads was the reason for the development of the crash cushion described herein. Design goals were:

(1) A total installation cost of less than $500.

(2) A barrier that would meet the requirements of the NCHRP Report 153 (Reference 3) except that the impact speed would be 30-35 mph.

(3) A device that would be non-proprietary.

The cushion, based on lunar landing technology, was developed as part of the Technology Transfer Program of the National Aeronautics and Space Administration (NASA), a program for adapting NASA technology to solve terrestrial problems in the public sector. Design and construction of the cushion, as well as instrumentation of the test vehicle and data analysis, were carried out by NASA's Jet Propulsion Laboratory engineers, under Contract NAS-7-100. All technology transfer functions, including cost/benefit studies and coordination, were performed by the Technology Applications Team at SRI International under Contract NAS-2-9846.

Table 1

FREEWAY OFF-THE-ROAD ACCIDENTS INVOLVING FIXED OBJECTS*

	Number of Accidents				
		Fatal		Injury	
	Total	Cars	Trucks	Cars	Trucks
Longitudinal gore delineators	55,000	500	100	17,600	5,200
Rigid poles	30,000	300	100	11,000	3,000
Rigid signs	20,000	200	--	4,200	1,100
Guard rail ends	16,000	200	100	4,500	1,500
Abutment, piers	11,000	400	100	3,700	1,000
Trees	7,000	100	--	2,500	400
Total	139,000	1,700	400	43,500	12,200

*Estimate based on a decision analysis by FCP, Project 1T, excludes nonfreeway accidents.

Table 2

NONFREEWAY ACCIDENTS INVOLVING FIXED OBJECTS*

	Number of Accidents				
		Fatal		Injury	
	Total	Cars	Trucks	Cars	Trucks
Longitudinal gore delineators	200,000	1,700	600	64,000	18,000
Rigid poles	240,000	2,300	800	76,800	26,800
Rigid signposts	240,000	600	200	14,000	3,800
Guard rail ends	100,000	9,000	300	27,000	10,000
Abutment, piers	50,000	1,600	400	18,000	5,100
Trees	114,000	2,000	400	39,000	8,700
Total	944,000	17,200	2,700	238,800	72,400

*Based on a decision analysis by FCP, Project 1T.

II. DESCRIPTIVE INFORMATION

NASA thoroughly researched impact attenuation before a lunar landing was attempted. The wealth of knowledge gleaned from this research has been tapped to develop a highway crash cushion having minimal or no disadvantages. The system is based on a concept disclosed in a NASA Tech Brief (72-10712) wherein many contiguous cylinders or spheres, arranged in multiple strata, attenuate an impact by sequentially crushing. The impact force is dissipated in a controlled manner.

Material selection was based on the results of a study made by NASA's Jet Propulsion Laboratory (JPL) (Knoell and Wilson, 1976). Various materials and configurations were comparison-tested for energy-dissipating characteristics; materials included glass, steel, aluminum, polypropylene, and polyethylene. As shown in Table 3, technical criteria used to determine energy-dissipating characteristics were the energy dissipated in crushing stress (σ_{CR}), the energy-dissipation density (E_D), and the stroke efficiency (e), which is the ratio of the "bottoming out" stroke to the original length. In addition, cost factors were estimated; the most interesting is the amount of crushable energy that could be dissipated for one cent (E_D).

With regard to performance and cost, the metal disposable beverage cans appeared to have the greatest potential application. Specifically, it was determined that for the same cost, the same amount of energy dissipated by crushing a 55-gal steel drum could be dissipated by crushing an array of 325 beverage cans of one-third the volume. This is emphasized because space limitation is an important consideration in placing crash cushions, particularly at tree and utility pole locations.

A one-module cushion was designed for use on low-speed roadways; i.e., 40 mph or less. The module is 3 ft. high, 45 in. wide, and 6 ft. long, and contains about 2,900 standard 12 oz. aluminum beverage cans. Cans in the rear half of the module, that is, the half adjacent to the tree or pole, are aligned axially. However, those in the front half are randomly oriented to provide a softer initial impact. (See Figures 1 and 2.) The aligned cans are taped in five rows that are 17 cans wide and 16 cans deep. A tear-proof, fire resistant, waterproof bag of polyvinyl chloride coated nylon contains the cans. Supporting the bag is a simple box frame of plywood sheathed with 18-gage steel sheeting. The front and sides of the module frame form one section that is unattached to the back and floor, which form another section. Upon impact, the front and sides slide backward, as the cans are crushed, the sides sliding past the backstop and tree as shown in Figure 3. Two 7-ft. long, wooden 4 x 6 posts, which fit into slots on the far side, prevent cushion rotation upon impact. Nor further preparation is required for installation. The materials and quantities needed are as shown in Figure 4.

The total cost for materials is approximately $150. Total weight for the 6-ft. module is less than 300 lbs.

If the unit were purchased, rather than constructed by highway personnel, the cost per unit would increase to about $500:

	Cost per Unit
Materials	$150
Equipment	0
Labor (3 hr @ $8/hr)*	24
Overhead @ 125%	40
TOTAL COST	$214
Plus profit at 50% of cost	107
Plus 48% corporate tax	96
SUGGESTED SELLING PRICE	$417

Plus ground preparation and installation costs of about $100.

*This hourly rate includes employee benefit costs, such as sick leave, vacation, and insurance.

Table 3

EVALUATION OF ENERGY-DISSIPATING CHARACTERISTICS OF VARIOUS MATERIALS

			Energy-Dissipating Characteristics			Cost Factors		
Category	Item	Material	E_D (in./lb)	σ_{CR} (lb/in.^{2})	$\bar{E}_D$ (in.-lb/in.^{3})	e, (%)	C_U $ est.	E_D (in.-lb/c)
Drums	55-gal drum	Steel	108,000	8	9	71	10.00	108
Spheres	Sphere, 2.5 in. diam x 0.035 in. wall	Glass	8	1	1	98	0.50	0
	Lightbulb, 2 in. diam x 0.020 in. wall	Glass	4	1	1	98	0.30	0
	Sphere, 4 in. diam x 0.040 in. wall	Polypropylene	590	15	18	80	0.80	7
	Sphere, 4 in. diam x 0.040 in. wall	Polyethylene	720	18	22	80	1.00	7
	Sphere, 8 in. diam x 0.065 in. wall	Steel	77,500	25	290	81	10.00	78
	Sphere, 4 in. diam x 0.040 in. wall	Aluminum	4,850	97	135	83	5.00	10
	Sphere, 8 in. diam x 0.025 in. wall	Aluminum	6,500	20	25	79	5.00	13
	Sphere, 13.5 in. diam x 0.065 in. wall	Aluminum	83,000	50	65	86	10.00	83
Disposable containers	12-oz beverage can	Aluminum	560	24	23	76	0.03	190
	12-oz beverage can (axial)	Aluminum	340	8	14	72	0.03	110
	16-oz beverage can	Aluminum	530	14	18	83	0.03	180
	12-oz beverage can	Steel	980	35	43	83	0.03	330
	12-oz beverage can (axial)	Steel	1,340	27	53	80	0.03	450
	30-lb refrig can	Steel	67,000	90	95	83	0.50	1340
	8-oz beverage bottle	Glass	12	1	1	95	0.06	1
Other	4 in. diam cylinder float	Copper	460	10	46	82	4.00	1
	3 in. diam muffin cup	Aluminum	140	7	5	92	0.03	47
	2 in. domed cylinder	Steel	9,200	960	1,010	66	0.60	150
	4 x 6 x 4 in. deep block: 1 lb/ft^3	Styrofoam	1,400	19	14	77	0.056	250

E_D = usable energy dissipated.
σ_{CR} = average crushing stress (avg. crushing force/max. cross-sectional area).
$\bar{E}_D$ = energy dissipated per unit volume.
e, = stroke efficiency.
C_U = estimated unit cost.
E_D^* = energy dissipated per penny.

Source: Jet Propulsion Laboratory

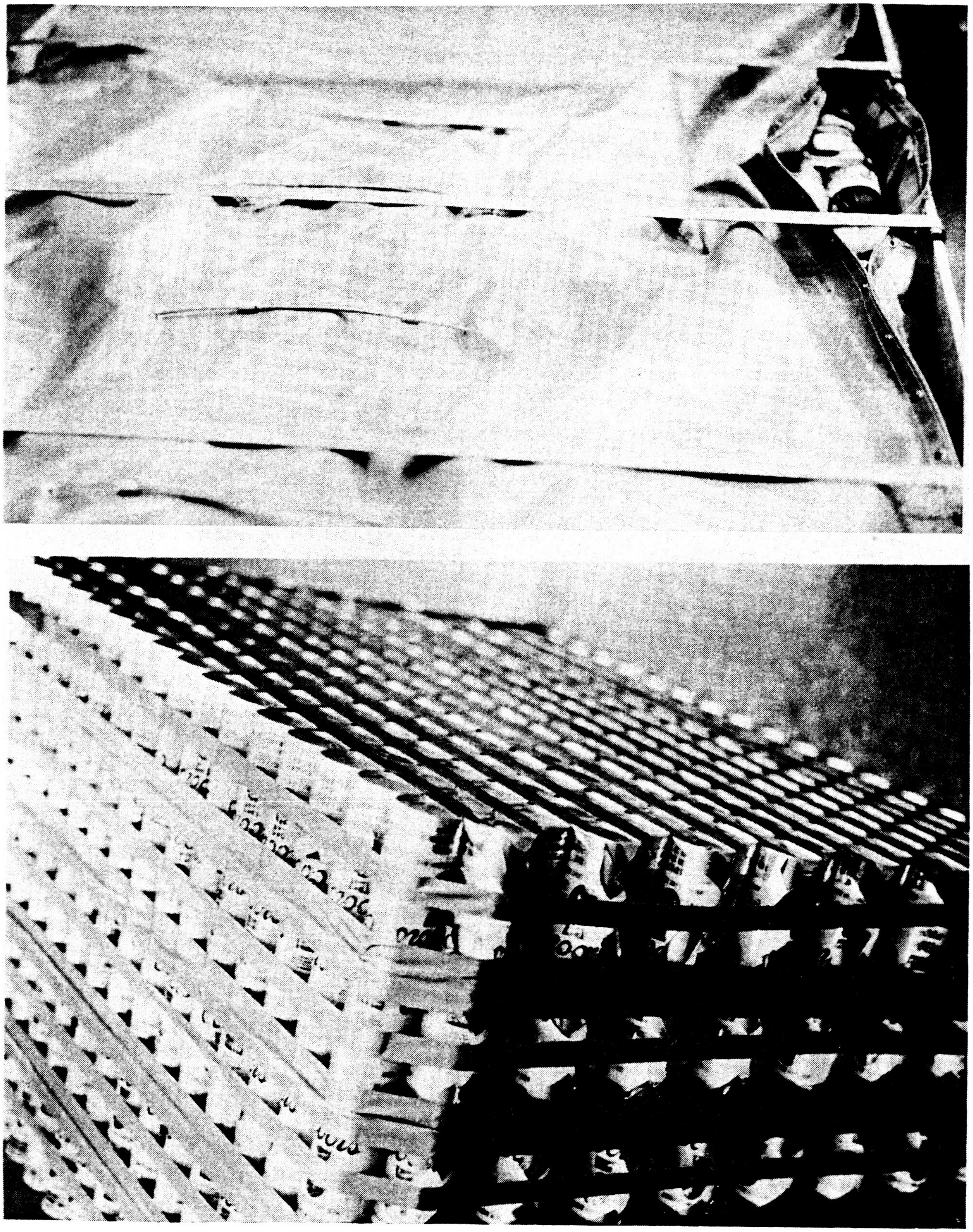


Figure 1. Heart of NASA's One-Module Crash Cushion

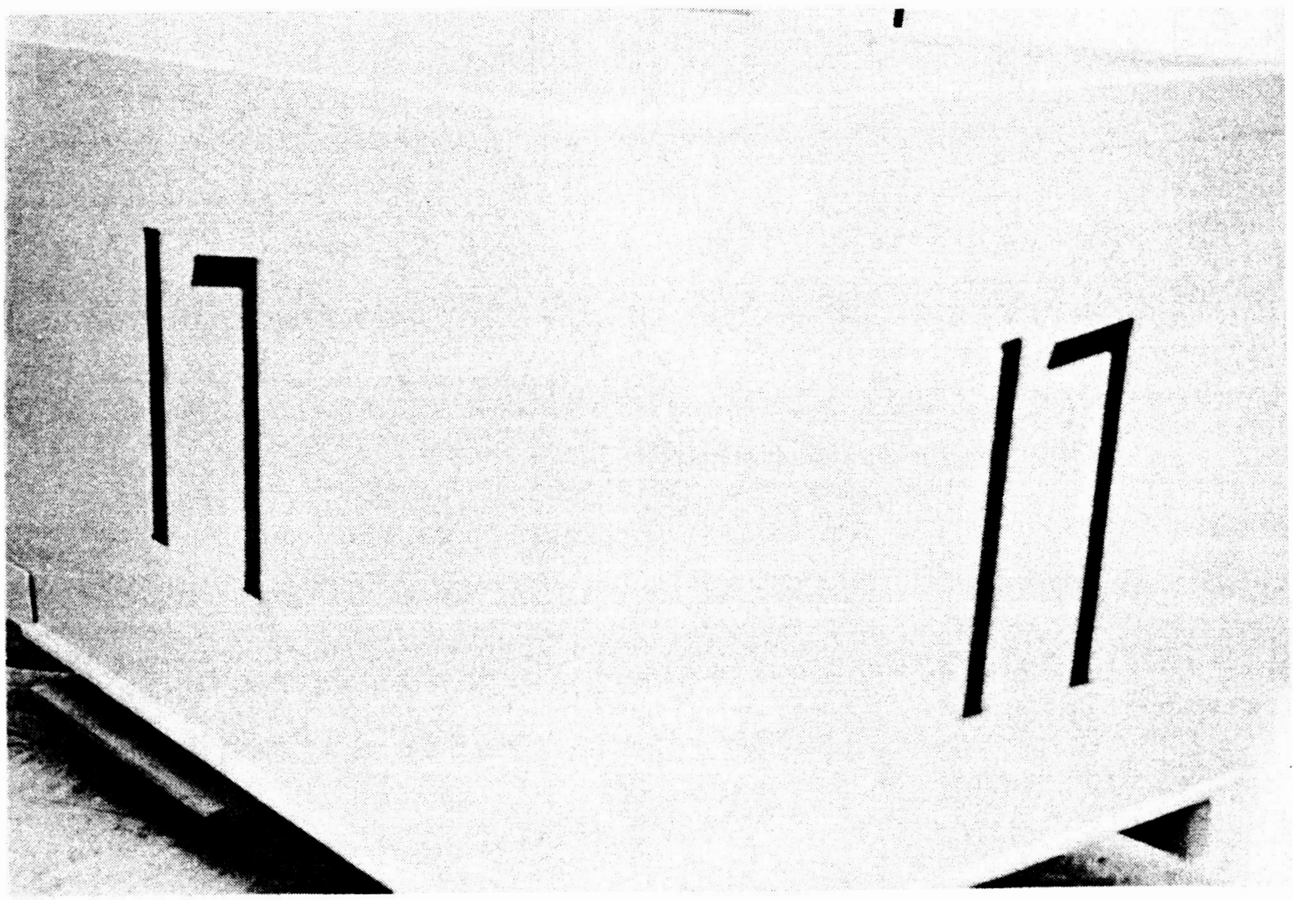


Figure 2. Frame for NASA Crash Cushion

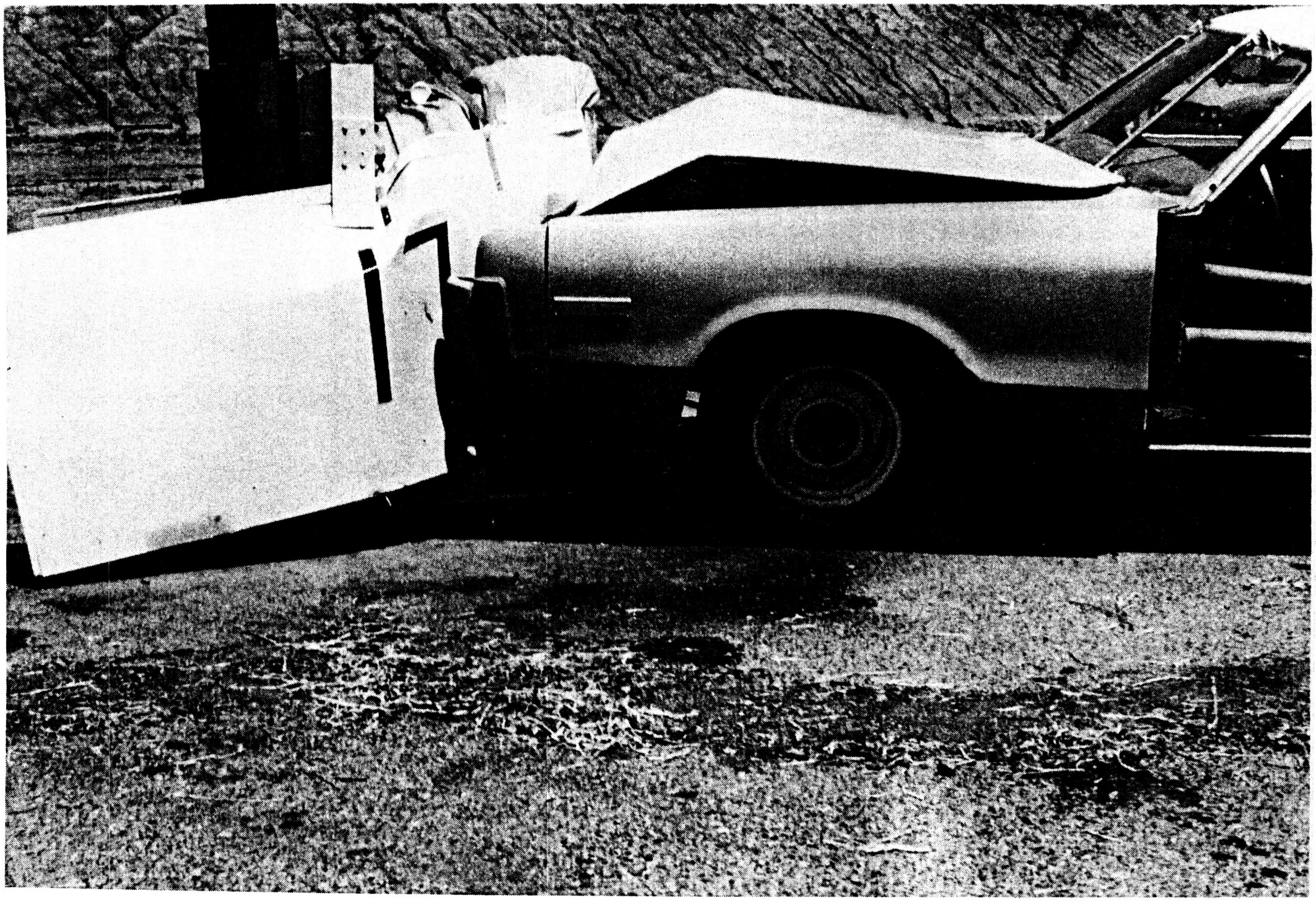
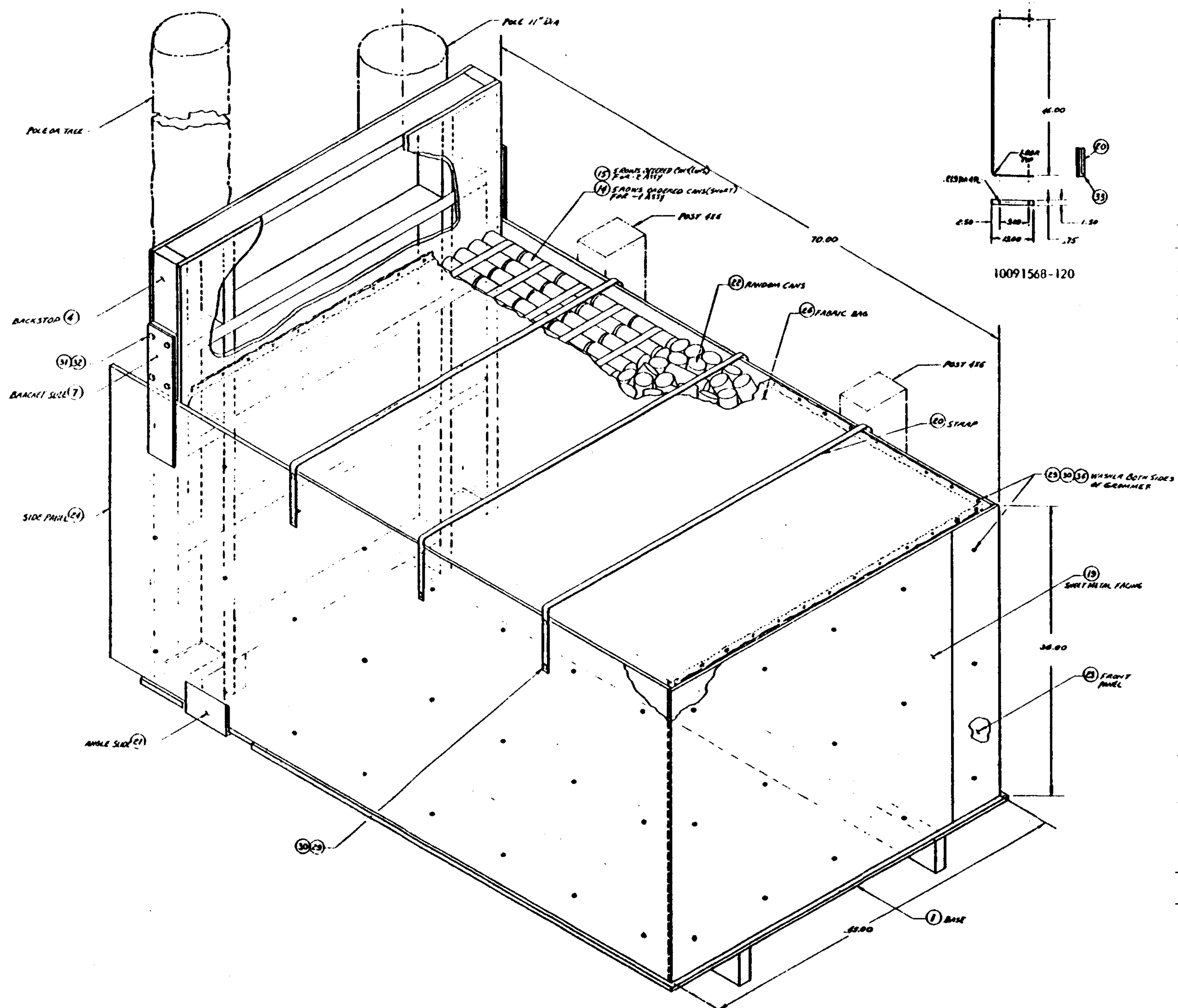


Figure 3. Performance of NASA Crash Cushion During 30-mph, 15^{o}-Angle Impact



NOMENCLATURE OR DESCRIPTION	SPECIFICATION	MATERIAL OR NOTE	ZONE
WASHER		1 1/4 OD X #10 ID X .016 THK	
TAPE 2" WIDE			
NUT		1/4	
SCREW, MACHINE		1/4	
NUT		#10-32	
SCREW, MACHINE		#10-32 X 3/4 LG	
CLIPS			
CABLE, TIE DOWN			
BAG			
BAG, END PANEL			
SIDE PANEL		3/8 X 35 X 80	
FRONT PANEL		3/8 X 45 X 36	
CANS, RANDOM			
ANGLE, SLIDE			
STRAP	CONSISTS OF ITEM 20 & 33	GALVANIZED 18 GAGE	
SHEET METAL FACING		GALVANIZED 18 GAGE	
TAPE, 1" WIDE			
CAN, LONG		2 1/2 OD X 5 1/4 LG	
CAN, SHORT		2 1/2 OD X 4.75 LG	
ORDERED CANS, LONG			
ORDERED CANS, SHORT			
GROMMET		00	
THREAD		STAR ULTRA-D NATURAL #12 DACRON	
FABRIC		PVC-1800 LAMINATED NYLON FABRIC	
BAG, FLAT			
SPACER		3/4 X 4 X 6	
PLATE		1/4 X 4 X 12 AL-2024-T3	
BRACKET, SLIDE			
2 X 4		370" TOTAL LENGTH	
PLYWOOD		1/2 X 45 X 57 1/2	
BACK STOP		1/2 X 45 X 53 1/2	
2 X 4		76 LONG	
PLYWOOD		1/2 X 48 X 76	
BASE			

Figure 4. Crash Barrier
(From JPL Drawing No. 10091568)

III. TEST PROGRAM

During 1978 and 1979, fourteen modules were built and crash tested in accordance with the National Cooperative Highway Research Program (NCHRP) Report 153. The test program included ten pretest crashes as well as the four tests required for evaluating a crash cushion. Report 153 states that "for lower speed roads it may be appropriate to design special crash cushions for lower impact velocities. It is recommended that these lower-impact-velocity crash cushions be evaluated at 110 percent of the posted speed limit for the four tests, instead of 60 mph." For NASA's one-module system, the four tests were adjusted as follows:

- Test 1: [4,500-lb. (2,040 kg.) vehicle/30 mph (13.4 m/s) /0 deg into center nose of device.]
- Test 2: [2,500-lb. (1,020 kg.) vehicle/30 mph (13.4 m/s) /0 deg. into center nose of the device.]
- Test 3: [4,500-lb. (2,040 kg.) vehicle/30 mph (13.4 m/s) /5 deg. into the corner of device.]
- Test 4: [4,500-lb. (2,040 kg.) vehicle/30 mph (13.4 m/s) /15 deg. impact angle into nose/2 ft. off-center.]

Test 3 adjustments were necessary due to the small size of the cushion, as well as the lower speed.

Laboratory Tests

Experimental activity at the Jet Propulsion Laboratory (JPL) in Pasadena, California, concentrated on testing the beverage can concept by determining the crushing characteristics of a single can first, and then of a multiple-can arrangement. The results of these tests, using a compression test facility, are provided in Table 4. These data were used in designing the full-scale module, with its cans oriented parallel to the main direction of crush. With this configuration, a significant amount of crushable energy could be obtained at a known and desireable force.

Field Tests

Full-scale modules built by JPL were crash tested at the Orange County Raceway in Irvine, California between August 1978 and July 1979. The tests were performed by a live driver from California Automotive Research. JPL did the instrumentation, both accelerometric and optical, and supervised the test program. The test track, part of the warm-up area behind the raceway, is approximately 60 ft. wide, with an additional shoulder width of 60 ft. The surface is completely flat, with no obstruction, curbs or ditches. The test area encompassed a 3,000-ft. stretch of the straightaway, with the space required to accelerate the vehicle to speed being 450 ft. Standard utility poles, with 11-12 in. diameters, were used for the preliminary tests. However, shearing of the wooden poles was noted when vehicle impact speeds reached 30 mph. For the final tests, 6-in. ID steel poles with 0.5-in. walls, were substituted to assure cushion performance during collisions with large, well-rooted trees. All poles were embedded to a depth of 6 ft. Pole centerline location was 24-in. from the road edge.

One of the primary applications for NASA's one-module crash cushion -- the prevention of collisions with utility poles on mountain roads where shoulders are narrow -- influenced the design of the test program. Test runs could be made axially or off-center, in or out of alignment of cushion nose. Cushions could be placed at a 15-deg. angle to the roadway, with the distance between cushion edge and roadway edge being adjustable.

Fifteen modules were crash tested during six days of testing, spaced about 60 days apart. The first four were preliminary-test days. Vehicle speeds for the first eight crashes ranged from 15 mph to 22.5 mph to assure driver safety. Lateral and longitudinal accelerometers were attached to a mounting block, which was secured to the vehicle in accordance with NCHRP Report 153 and with Transportation Research Circular 191. Final tests were made at 30 mph. Results of these tests appear in Figure 5 through 7, and the calculated G level in Tables 5 through 8. Although the duration of impact was always equal to or greater than 300 miliseconds average accelerations were calculated for 50, 100 and 300 miliseconds. Average G levels were within the 6.0 preferred levels set by both NCHRP and AASHTO (American Association of State Highway and Transportation Officials), and well within the 12.0 limit (see Table 9). At no time did bottoming of the cushion occur. Examination of the cans after impact revealed that in every case at least an additional foot of compression of the cans was possible without bottoming. Damage to the vehicle was always limited to the radiator, grill and fender(s), with no cracked windows, no blown tires and no injury to the driver; head-on crashes into the nose of the device (cushion) resulted in only a denting of the grill and hood. The vehicles were 1973 Dodge Polaras and a 1978 Datsun B210, with ballast.

Calculations were also made of the G levels to be expected at 40 and 45 mph (Figure 8). A 4500-lb. vehicle impacting the module with a 6-ft. stopping distance (crushing of barrier and car) at 40 mph would register average G levels of about 11.4. From an energy absorption standpoint, the 4,500-lb vehicle traveling at 30 mph (44 ft/sec) has a kinetic energy of

$$1/2 \cdot \frac{4500}{32.2} \cdot 44^2, \text{ or } 135,280 \text{ ft lb.}$$

Assuming that the average force acts for the entire 6 feet of travel, the force is $\frac{135,280}{6}$ or 22,546 lb.

If the same force were to act for an additional foot of travel distance, the energy absorbed would be increased by 17% (7/6 = 117%). This corresponds to a velocity increase of 8.0% ($\sqrt{1.17}$ = 1.083). The impact speed would then be about 32.4 mph (1.08 x 30 = 32.4).

However, assuming the average force, (and hence the average G level) were also increased as bottoming is approached, and assuming this increase were by 50%, then for a 7-ft. travel, the energy absorbed would increase by 76% (1.5 x 1.17 = 1.76); the corresponding impact speed would be ($1.7^{1/2}$ x 30) $\simeq$ 39.8 mph. This would correspond to a 7.6 G acceleration for a 7-ft travel with an impact speed of 40 mph.

As indicated earlier, this is well below the allowable 12 G average acceleration and is believed to be a reasonable extrapolation. It is therefore believed that the barrier is safe for a 40 mph crash.

An additional crash test was conducted at 31 mph, head-on into the cushion nose using a 4,500-lb. vehicle. The resulting G levels, as shown in Figure 9 and Table 10, confirm the calculation made in Figure 8.

Of additional interest are the accelerometer readings for the helmet (Figures 10 and 11) which seem to indicate that the driver is subjected to higher G levels than is the vehicle. In all but the first crash test, the helmet accelerometer registered G levels that exceeded the chart limit of 10.0 for as much as 75 miliseconds. A comparison of the data in Tables 5 and 10, for head-on crashes of 4,500-lb. vehicles at 30 and 31 mph, respectively, reveals that although average G levels for the vehicle were 7.0 and 8.8 for 50 ms, those for the helmet were 12.0 and 21.0. That is, G levels for the helmet were at least 25% higher. Average G levels for 300 ms were equivalent, however. These higher levels were assumed to result from head rotation, which occurred in spite of the racing harness worn by the driver. High-speed photography confirmed this assumption that the driver experienced significant head rotation. (Doors were removed from the vehicles -- and replaced by bars -- to facilitate driver escape and to accomodate photographing of the driver.) This finding, not included in this project's objectives, may indicate a need for further studies on the relationship between vehicle impact data and driver/ passenger data.

Table 4

Scaling factors: ratio of multiple element to single element data

Item	Material	Scaling factors			
		E_D	σ_{CR}	$\bar{E}_D$	ϵ
Top layer 6 Middle layer 7 Bottom layer 7 Total 20 sphere, 4" diam x 0.40" wall	Polyethylene	0.85	0.69	0.82	0.94
Top layer 6 Middle layer 7 Bottom layer 7 Total 20 sphere, 4" diam x 0.040" wall	Aluminum	0.61	0.74	0.61	0.75
Top layer 5 Middle layer 5 Bottom layer 5 Total 15 sphere, 8" diam x 0.025" wall	Aluminum	0.72	1.85	0.72	0.85
Top layer 5 2nd layer 5 3rd layer 5 4th layer 5 5th layer 5 Total 25 12-oz beverage can	Steel	0.94	1.09	0.81	0.89
Top layer 5 2nd layer 5 3rd layer 5 4th layer 5 5th layer 5 Total 25 12-oz beverage can	Aluminum	0.78	0.85	0.72	1.00

TABLE 5

TEST RESULTS: 4,500-LB VEHICLE/30 MPH/
0 DEG INTO CENTER NOSE OF DEVICE

ACCELEROMETER LOCATION	MAX Gs	AVERAGE Gs 50 MS	100 MS	300 MS
FRONT FLOOR BLOCK	9.5	7.5	6.7	4.8
REAR FLOOR BLOCK	10.0	6.5	6.1	4.6
HELMET	10.5	8.5	7.2	4.2

TABLE 6

TEST RESULTS: 2,250-LB. VEHICLE/30 MPH/
0 DEG INTO NOSE OF DEVICE

ACCELEROMETER LOCATION	MAX Gs	AVERAGE Gs 50 MS	100 MS	300 MS
FRONT FLOOR BLOCK	9.5	7.0	6.1	4.9
	10.0	7.0	6.0	4.5
REAR FLOOR BLOCK	12.5	6.5	6.1	4.4
	12.0	8.0	6.0	5.3
HELMET	*	*		

*RECORDING EXCEEDED CHART LIMITS.

TABLE 7

TEST RESULTS: 4,500-LB. VEHICLE/30 MPH/
15-20 DEG ALONGSIDE DEVICE

ACCELEROMETER LOCATION	MAX GS	AVERAGE GS 50 MS	100 MS	300 MS
FRONT FLOOR BLOCK	11.5	7.0	6.0	4.2
REAR FLOOR BLOCK	11.5	7.5	6.1	4.8
HELMET	12.5	12.0	9.5	5.5

TABLE 8

TEST RESULTS: 4,500-LB VEHICLE/
30 MPH/10-15 DEG INTO
NOSE OF DEVICE,
2 FT. OFF CENTER

ACCELEROMETER LOCATION	MAX GS	50 MS	100 MS	300 MS
FRONT FLOOR BLOCK	11.5	9.5	7.7	5.2
	11.0	7.5	7.0	4.7
REAR FLOOR BLOCK	12.0	10.0	9.0	6.1
	10.0	7.5	7.1	4.9
HELMET	10.+*	*		

*RECORDING EXCEEDED CHART LIMITS.

Table 9

Average G Levels for Required Tests

Test Description	Average Gs 50 ms	100 ms	300 ms
4,500-lb Vehicle; 30 mph/0 deg into Center Nose of Device	7.0	6.4	4.7
2,250-lb Vehicle; 30 mph/0 deg into Nose of Device	7.1	6.1	4.8
4,500-lb Vehicle; 30 mph/15-20 deg alongside of Device	7.3	6.1	4.5
4,500-lb Vehicle; 30 mph/10-15 deg into Nose of Device, 2 ft. off Center	8.6	7.7	5.2

Table 10

TEST RESULTS: 4,500-lb Vehicle/34 mph/ 0 deg into Center Nose of Device

Accelerometer Location	Max Gs	Average Gs 50 ms	100 ms	300 ms
Front Floor Block	12.5	9.0	8.0	4.8
Rear Floor Block	13.0	8.5	7.0	4.9
Helmet	32.0	21.0	12.5	5.8

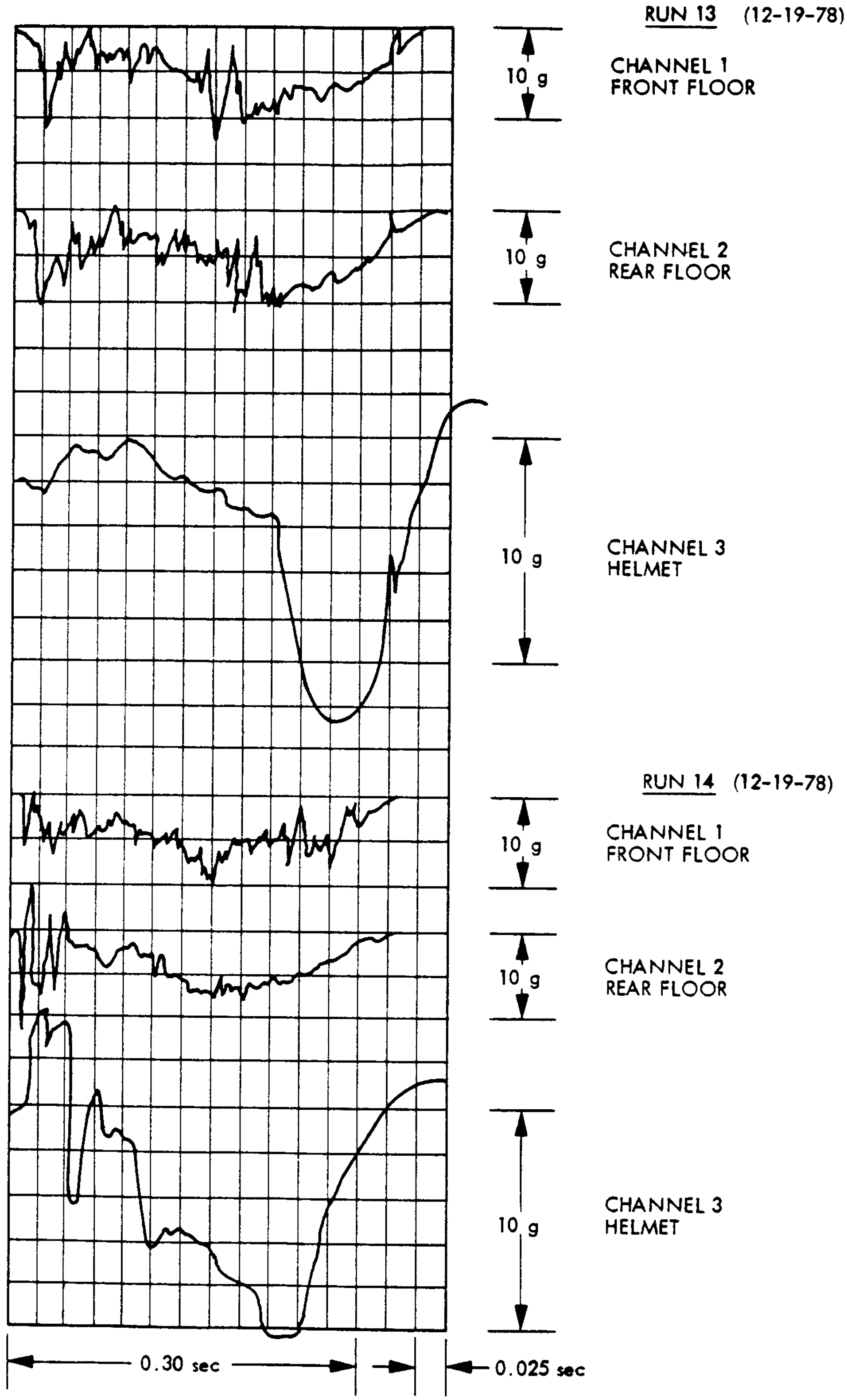


Figure 5. Accelerometer Traces; Run 13 and Run 14

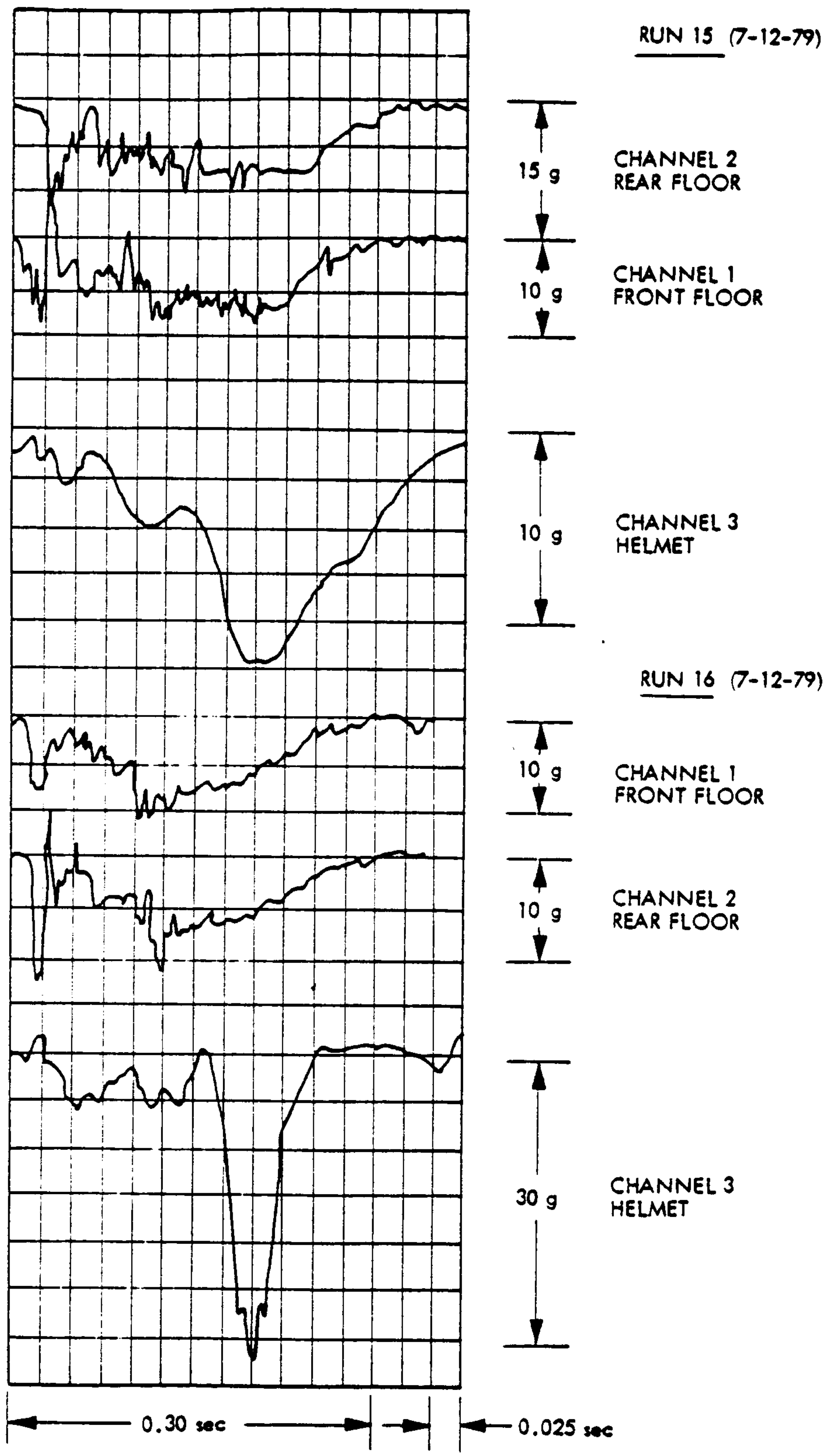


Figure 6. Accelerometer Traces; Run 15 and Run 16

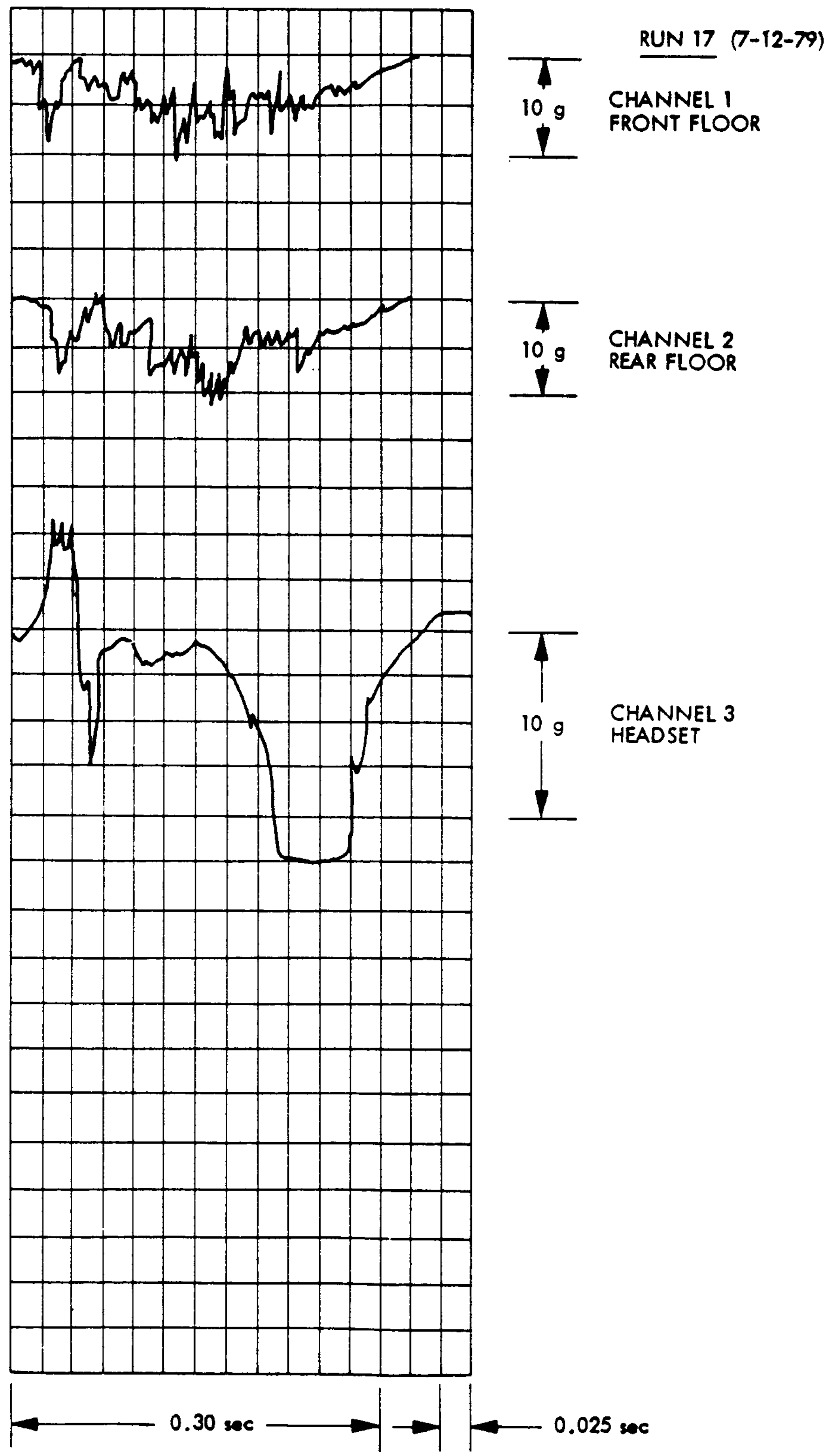


Figure 7. Accelerometer Traces; Run 17

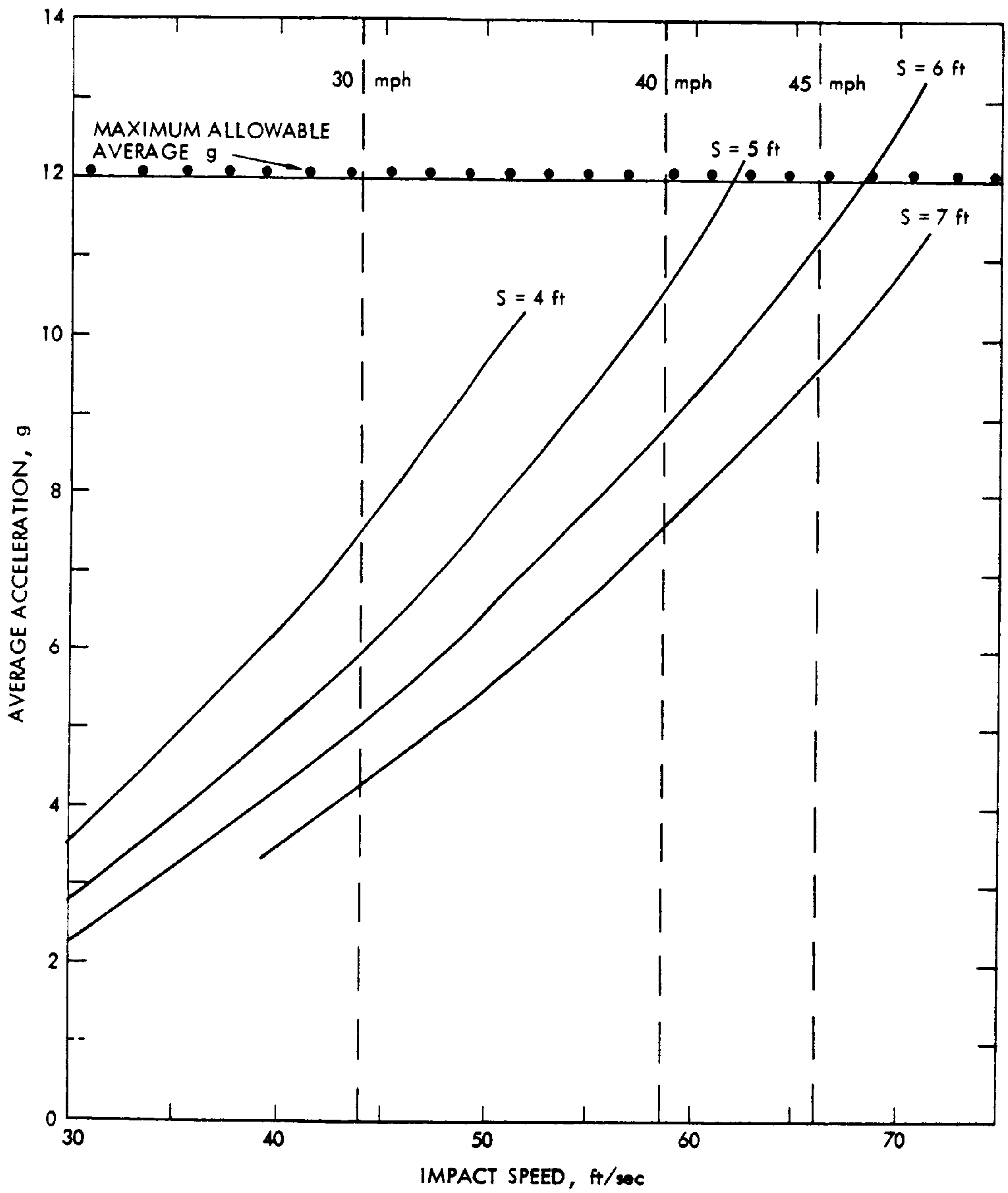


Figure 8. Average g vs Impact Speed

IV. COST ANALYSIS

In selecting a crash cushion, the highway engineer weighs collision repair costs and regular upkeep costs against initial costs. Therefore, all three costs must be considered in a cost analysis. Comparisons are made with 20-ft. systems that are currently available in the marketplace.

Initial Costs

Based on 1977 bid prices of installations designed for 60 mph impacts, the California DOT first-cost estimates are given below. Ranges are given to accommodate variations in geometric design. That is, although installations were of the same length, one would be costlier than another if it were wider or if site preparation were extensive

	Installation Costs (dollars)
Sand barrels	$5,000-7,000
Water-filled sandwich	17,500-21,000
Steel drums	9,000-10,000
Vermiculite concrete cartridges	18,000-21,000

The average cost for installation of the NASA system of the same size is expected to be $2,500 (3 modules plus installation costs). According to the AASHTO, national averages are much lower primarily because of lower labor costs; however, costs for the NASA crash cushion are being compared with the California averages, because the cushion was developed in California at California rates.

Collision Repair Costs

Most postconstruction costs for crash cushions are incurred as a result of accidents. Therefore, despite a high initial cost, a crash cushion with low repair costs may be most cost-effective for locations having a history of numerous crashes. Based on data collected by the California DOT, a tabulation was made (Table 11) that reviews system costs from a combined position of installation and repair. Because systems are often replaced after 10 hits, to preserve the structural integrity of the unit, a 10-hit life has been assumed for each system.

Table 11

COST COMPARISON OF IMPACT ATTENUATORS

Device	Bid Price + (dollars)	Average Repair Cost x (dollars)	Hits per Unit	Repair % of Bid*	Total Cost($)
Sand barrels	7,000	1,218	10	17.4	19,180
Water-filled sandwich system	21,000	252	10	1.2	23,520
Vermiculite concrete cannisters	21,000	420	10	2.0	25,200
Steel drums	10,000	930	10	9.3	19,300
NASA beverage-can system	2,500†	325**	10	17.4	5,750

*Based on California DOT data (1970-1977).

†Estimated cost for 3-module system.

**Arbitrary use of highest percent for other systems (17.4%), less $100 salvage.

A ten-hit life is equal to 10 years (average of 1 hit per year). Total repair costs are derived by adding initial costs to the average repair costs multiplied by the 10 hits. No inflationary factor has been inserted for the 10 years.

Regular Maintenance Costs

Costs are regularly incurred for checking water levels in water-filled systems and adding anti-freeze in cold climates, removing the debris that collects in cabled and fendered systems, adding salt to the sand barrels to prevent caking, and for vandalism. All systems are subject to vandalism, but the water-filled cluster is especially vandalized because of its attractiveness to sharpshooters who like to puncture the unprotected vinyl cells and effect a spouting of the water. (Water filled cells in sandwich system are protected by the redirectional fenders.)

Based on the assumption that 1 man-hour per month per cabled/fendered system is required for hardware checks and debris removal and that water levels are checked weekly and require another 1 man-hour per month per system of labor time, annual costs for routine maintenance can be estimated. During its 10-year life,* the average water-filled system will cost $1,080 for debris removal, another $1,080 for water-level checks, as much as $3,000 for ethylene glycol, and about $500 for cluster cell replacement due to vandalism for a total noncollision maintenance cost of $2,660 (no antifreeze) to $5,660.† Sand-barrel installations must be checked for correct barrel positions and sand levels which requires about 1 man-hour per month per system, or $1,080 for a 10-year period. (The sand-barrel installation does not have a 10-year life; by design it disintegrates and part or all of the barrels must be replaced after each impact.) Vermiculite concrete systems require only debris checks ($108/yr) and occasional painting (about 2 man-hours per year at $15/hr) for a 10-year cost of $1,380 per system. Because of their susceptibility to corrosion from deicing salts and other agents, steel drums may require repainting on a regular basis as well as debris removal, estimated at 1.5 man-hours per system per month or $1,620 for a 10-year period. Thus, the cost comparisons are revised as follows:

	Average Total Cost (10-yr life)
Sand barrels	$20,260
Water-filled sandwich	26,180
Vermiculite concrete cannisters	26,580
Steel drums	20.920

Routine maintenance for the NASA system is expected to include debris cleanup and repainting which require 1.2 man-hours per month or $1,380 for 10 years, for a total of $7,130. For the one-module system the expected 10-year cost would be about $2,000.

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*Accidents average 1 per year per crash cushion; hence, 10 accidents equal 10 years.

†Based on 1978 maintenance costs.

V. CONCLUSION

NASA's crash cushion is a small (3.25 x 3 x 6 ft.) one-module system for use on roadways of 40 mph or less. Its light weight (300 lb.) and the absence of anchor cables mean easy installation. Low G levels, averaging about 4.8, and low material costs of about $150, should lead to widespread use as an impact attenuator for utility poles on all roadways and as an all-purpose impact attenuator for low-speed roadways. Because this technology was developed by the federal government, it is non-proprietary and use of it is encouraged. However, if units are to be constructed for profit, rights to the patent (U.S. Patent 4,118,014) should be obtained from the NASA Patent Office.

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